Geological Society of America Bulletin, 1997, v.109, p. 1617-1630.

Amanz Gressly's Role in Founding Modern Stratigraphy

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Abstract

This paper discusses Amanz Gressly's (1814-1865) fundamental contributions to stratigraphy in three areas: facies concepts and applications, stratigraphic correlation, and paleogeographic reconstruction. To facilitate access to his discoveries, we present an English translation of his paper (Gressly, 1838) on facies and stratigraphic correlation. We discuss excerpts from this translation which demonstrate that many of the fundamental principles of modern stratigraphy were understood and expressed by Gressly. We put this into the context of subsequent development and refinement of current stratigraphic principles.

Gressly explained the genesis of sedimentary facies by processes operating in depositional environments. He demonstrated regular lateral facies transitions along beds which he interpreted as mosaics of environments along depositional profiles. He recognized the coincidence of particular fossil morphologies with particular sedimentological facies, and distinguished "facies fossils" from those which had time value and which were useful for biostratigraphy ("index" or "zone" fossils). He discussed the equivalency of vertical facies successions through a series of strata and lateral facies transitions along a bed, developing the same principle that later became known as Walther's Law of the Correlation of Facies. He distinguished between the time value of strata and properties which reflect their genesis, and introduced specific terms to reflect this distinction. He used this understanding to show how stratigraphic successions should be correlated across different facies tracts.

Gressly derived an internally consistent, logical and comprehensive definition of a new stratigraphic paradigm which was the basis for further developments and refinements. The five remaining principles of contemporary stratigraphic thought include: (a) the stratigraphic process-response system conserves mass; (b) sediment volumes are differentially partitioned into facies tracts within a space-time continuum as a consequence of mass conservation; (c) cycles of facies tract movements laterally (uphill and downhill) across the earth's surface are directly linked to vertical facies successions, and are the basis for high-resolution correlation of stratigraphic cycles; (d) stratigraphic base level is the clock of geologic time, and the reference frame for relating the energy of space formation with the energy of sediment transfer; and (e) facies differentiation is a byproduct of sediment volume partitioning.

Introduction

While other geologists were attempting to solve the structure of the Jura Mountains, Amanz Gressly (1814-1865), a Swiss geologist, was intent on unraveling the paleogeography of the deformed strata. In doing so, Gressly discovered and stated many of the principles which are the foundations of modern stratigraphy. Despite numerous obituaries, short historical discussions, and fuller biographies—principally in German-Swiss literature and principally focused on the history of the region in which he lived and worked—his fundamental contributions are not well known to earth scientists. This paper focuses on his contributions to stratigraphic science in three areas, facies concepts and applications, stratigraphic correlation, and paleogeographic reconstruction.

Although Gressly is widely credited with the first modern use and definition of "facies" (Dunbar and Rodgers, 1957; Teichert, 1958), his contributions to stratigraphic principles are much broader and deserve greater appreciation. He explained the genesis of sedimentary facies by processes operating in depositional environments, and demonstrated regular lateral facies transitions along beds which he interpreted as mosaics of environments along depositional profiles. He recognized the coincidence of particular fossil morphologies with particular facies, and distinguished "facies fossils" from those which had time value and which were useful for biostratigraphy ("index" or "zone" fossils). He discussed the equivalency of vertical facies successions through a series of strata and lateral facies transitions along a bed, developing the same principle that later became known as Walther's Law of the Correlation of Facies. He distinguished between the time value of strata and properties which reflect their genesis, and introduced specific terms to reflect this distinction. He used this understanding to show how stratigraphic successions should be correlated across different facies tracts. Gressly supplied the concepts which replaced the foundering paradigm of Wernerian Neptunism, and established many tenets of modern stratigraphy. His insights were relevant as much to the fields of paleontology, paleobiology, paleoecology and evolution as they were to stratigraphy.

One purpose of this paper is to increase awareness of Gressly's contributions to the foundations of stratigraphy. To this end, we present an English translation of his 1838 paper on facies and stratigraphic correlation. We also summarize his statements about and understanding of fundamental stratigraphic principles, and place them into the context of contemporary stratigraphic thought. With a knowledge of the philosophies and methods Gressly imparted to geologists of his time, we can identify the few subsequent additions to Gressly's "Laws" that completed the foundation of stratigraphic science. Thus, a second purpose of this paper is to show that many of the fundamental stratigraphic principles were established early in the practice of stratigraphy.

Providing a New Paradigm to Replace Werner's Neptunist Concept

Gressly established a novel methodology and philosophical approach to stratigraphic analysis that replaced Werner's Neptunist concept. Although the Neptunist concept already had been challenged and abandoned by some of his contemporaries (for example, see commentaries in Conkin and Conkin, 1984), Gressly offered the alternative concepts and methods which were to become the foundation of modern stratigraphy. Kuhn (1962) argued that new paradigms in science follow a period of discomfort with the existing paradigm because of mismatches between observation and theory; Gressly did his studies during such a period of discomfort.

Gressly's insightful departure from the existing paradigm contained three fundamental, related concepts. First, he recognized that the sedimentologic and paleontologic attributes of rocks, "facies," reflected the processes of deposition within specific geomorphic environments. Second, he understood that facies occur independently of time, and that time and rocks must be treated with separate concepts and vocabularies. Third, he established that there are predictable patterns of facies relationships. He documented that facies occur in regular patterns of lateral transitions along a bed, and that these lateral transitions are repeated in vertical successions. This work was accomplished during his early twenties from observations made on discontinuous, vegetated outcrops, and without the benefit of much formal geological training.

Important reviews of Gressly's education, collaboration with his contemporaries, work in the Jura, contributions to stratigraphic science and other biographical information are given by Teichert (1958), Wegmann (1963), Meyer (1966), Nelson (1985), Stampfli (1986) and Schaer (1994). Gressly was born in the village of Bärschwil (Canton de Solothurn) in the German-speaking area of Switzerland near the outer, northwestern thrusts of the Jura Mountains. After pre-University schooling in Solothurn, Luzern, and Fribourg, he spent several months in Porrentruy (Canton Bern), Switzerland, to improve his French. In November, 1834, at the age of 20, he went to University of Strasbourg to study medicine. While there he attended lectures on geology given by Phillippe Voltz, the chief engineer of the Strasbourg mineral district. He became friends with Julius Thurmann, a professor of mathematics and natural science at Porrentruy who also was studying geology under Voltz in Strasbourg. Thurmann's research was on the stratigraphy and structure of the Bernese Jura. He encouraged Gressly to initiate parallel and complementary studies in the adjacent Soloturn Canton to the east.

In July, 1836, after two years of field work in the Solothurn Jura, Gressly went with Thurmann to Solothurn to present an oral paper at the annual meeting of the Swiss Natural History Society. The extended abstract of his paper was published the following year (Gressly, 1837). In this paper, Gressly gives a short definition of sedimentary facies, and he relates the facies he had observed to depositional environments. The first part of Gressly's major work, "Observations géologiques sur le Jura soleurois," was published in 1838, apparently with considerable help in composition and editing from his friends, particularly Thurmann.

At the Solothurn meeting, Gressly also met Louis Agassiz. Agassiz, the internationally respected paleontologist and geologist, recognized the novelty and importance of Gressly's insights and command of lithostratigraphic and biostratigraphic data. He encouraged Gressly to continue with his work. After publication of the first part of the "Observations," Agassiz promoted Gressly's work by circulating the paper widely. In evidence, during the session of the French Geological Society on 20 November, 1837, Marquis de Roys (a good friend of Prévost) reported on his work on terrains of the southwest Paris basin, ending with a comment that the *facies* of these terrains were determined by their aspect but not by their age (de Roys, 1837).

After the Solothurn meeting Gressly did not return to Strasbourg. Rather, he went to Porrentruy and stayed with Thurmann. In November, 1836, Gressly went to Neuchatel to follow lectures given by Agassiz until January, 1838. Subsequently, he was employed by Agassiz for several years as an assistant at the Museum of Neuchatel to collect and curate fossils. Gressly's fossil collection, carefully collected within a few years and recorded within a stratigraphic context, numbered more than 25,000 specimens. Between January, 1838 and September, 1839, Gressly was mentally ill, and there is an absence of correspondence from that period. This illness delayed publication of the rest of Gressly's "Observations" until 1840 and 1841. That Gressly did not publish subsequently on facies is attributed to his fragile health. The main part of his work, consisting of 75 scientific manuscripts, 57 field notebooks and myriad personal notes, is stored at the Museum of Solothurn (Stampfli, 1986).

Wegmann (1963) casts Gressly as a revolutionary in the context of "normal" versus "revolutionary" science, using terms formalized by T.S. Kuhn (1962). The prevailing geological notions of the time were derived from Werner's Neptunist concepts, in which formations were considered contemporaneous, globally distributed, specific rock types. By contrast, from empirical observation Gressly recognized that a specific rock type ("facies") reflects its origin in terms of environment and conditions of accumulation, not in terms of its age. Rocks of the same age change character ("facies") over distance (along depositional profiles), reflecting the changes in environments across a geomorphic landscape. And, rocks of the same types occur at multiple stratigraphic positions, reflecting the repetition of environments through time. Gressly made his observations and derived his insights from study of fossiliferous, shallow shelf and reefal limestones. It is possible that the diversity of facies and the abundance of the fossil assemblages allowed Gressly to observe and to understand the stratigraphic, paleoecologic and geomorphic significance of subtle variations in facies and their relations to time.

To emphasize the originality of Gressly's approach and his break from accepted stratigraphic practices, Wegmann (1963) and Teichert (1958) compared Gressly's concept of facies with that of his contemporary, Constant Prévost. Both Gressly and Prévost distinguished between the origin and physical attributes of a rock versus its age. Prévost, a rationalist, reached this conclusion using logical deduction, whereas Gressly followed an empirical path and observed the differences. In publications dating a few years after Gressly's paper, Prévost (1839, 1845) redefined two existing terms, "terrain" (designating rocks of different types but of the same age) and "formation" (comprising all sediments originating from a same depositional process or environment) to distinguish between the temporal and physical attributes of strata. By contrast, Gressly proposed an entirely different term, "facies," to separate clearly and distinctly the physical and biological aspects of rocks from their age.

Wegmann (1963) argued that the redefinition of existing terms was not sufficient to convey to their contemporaries this new understanding about the distinction between temporal and physical aspects of rocks. Instead, Wegmann concluded that Gressly's introduction of a different term was essential to emphasize the difference in concept. Gressly did not just redefine the term "facies," which was in use in several geological contexts by Steno (see Winter, 1930, and Friedman, 1990) and others (Conkin and Conkin, 1984; Markevitch, 1960; Nelson, 1985; Teichert, 1958). Rather, he introduced the means to express this new way of thinking about the separate temporal and physical aspects of rocks.

Recognizing Disorder and Confronting the Paradigm that Rock and Time are Inseparable and Equivalent

At the time Gressly began a study of Jurassic limestones in the French and Swiss Jura Mountains, stratified rocks [Werner's Secondary] in Great Britain and the Continent had been divided into large-scale stratigraphic units termed "terrains" and smaller scale units termed "formations." Terrains were considered global in distribution and of the same age, whatever their composition or inferred origin. Formations were classified and recognized by general lithologic characteristics and fossil assemblages which were thought to typify each unit throughout extensive regions. Because formations occurred in stratigraphic succession like terrains, formations were considered both time bounded and lithologically distinct. Recognition of a particular lithology was sufficient to define the age of the strata being examined. This perception of time-lithology equivalency maintained the Wernerian tradition which assumed lithologic identity and global constancy of paleoenvironmental conditions from one time period to the next.

Gressly initially intended to use the stratigraphic units which his colleague and mentor Thurmann had defined in the Bernese Jura, and to apply them to the Soleure Jura (see Wegmann, 1963). Thurmann had established stratigraphic divisions and correlations in the traditional manner, measuring a series of stratigraphic sections [type sections] and then correlating the strata between them. The correlations were based upon lithologic equivalency.

> "My intention was to apply to the country where I live the geological laws that Mr. Thurmann verified with so much talent and success on the stratigraphic units of the neighboring Bernese Jura; …" 10/21-23

However, comparisons of time-equivalent formations between Great Britain and the Continent, and within Switzerland and France convinced Gressly that formations were not lithologically uniform. Gressly identified regional differences in lithology among coeval stratigraphic units of formation and smaller scales. Also, he observed lithologic variability along beds, as well as differences in vertical lithologic successions at different geographic positions within strata in the Jura. Since the lithologies were not uniform within either formations or smaller stratigraphic units, then age equivalence could not be assigned on the basis of lithologic equivalence. His implicit understanding was that bed boundaries represent very high-resolution time surfaces; and, therefore, geographic changes of lithology along beds meant that the depositional conditions or environments also changed along a depositional profile.

In summary, Gressly recognized considerable lithologic variation within formations at both regional and local scales. He concluded that lithology could not be presumed an *a priori* proxy for time.

> "In the areas that I have studied, perhaps more so than anywhere else, extremely varied petrographical or paleontological variations interrupt at every step the universal uniformity that was ascribed until now to the different stratigraphic units in the different countries. They [these variations] are even repetitive in several strati-

> graphic units, and cause astonishment for the geologist who attempts to study the nature of our Jurassic ranges." 10/1-7

Gressly explicitly cautioned against assigning an age to strata based upon lithologic characteristics. He warned that since lithologic characteristics are sufficiently alike in stratigraphic units of different ages, a geologist can mistake the age of a unit if its age is judged by lithology. Similarly, he cautioned that since the same vertical successions of lithologies are repeated in multiple stratigraphic units, a geologist can consider several temporally distinct stratigraphic units as one.

> "Commonly, he [the geologist] will stop with surprise in front of formations he thought he knew well for a long time. Led astray by too much faith in accepted geological dogma, which often generalizes purely local facts, he will perhaps be mistaken about characters which until then he thought belonged only to a given stratigraphic unit and to a subdivision in particular; he even will be tempted to completely confuse several stratigraphic units going so far as to doubt their [separate] existence." 10/8-14

Not only did Gressly demonstrate that the same rock types occurred at multiple stratigraphic positions independent of formations and their boundaries, he also discovered that when he followed beds laterally a regular lateral succession of petrographical and paleontological attributes occurred along them. From these observations and considerations, Gressly determined he would have to establish a different sort of regional classification of stratigraphic units, one that did not assume lithologic constancy within formations. He realized this would require detailed mapping of the lithological changes within beds of formations. The detailed mapping would establish temporal equivalency of strata within formations, spatial variations in lithology within time-equivalent units, and the basis for inferring the paleogeomorphology of fine-scale time slices. This approach would establish the basis for stratigraphic correlations.

> "…but soon I was forced to successively modify these [Thurmann's] laws according to the diverse regions which make up the Soleure Jura, and the study of these diverse regions necessitated on my part a system of research [research method] different to the one which is generally practiced. Instead of being satisfied with a certain number of vertical sections as type sections ["types descriptifs"], I followed each stratigraphic unit [beds and subdivisions of formations] along its horizontal extent as far as possible in order to study all its variations." 10/21-29

In these passages, Gressly recounts his changing perceptions about the approaches and philosophies required to study the stratigraphy of the Jura. Originally, he intended to conduct stratigraphic research using the existing paradigm and methods, but he discovered that they did not work and were specifically contradicted by his observations. He empirically evaluated those concepts and methods which required modification in order to honor both the data and his understanding of the distinction between time and facies. Within this evolution of changing perceptions and practical approaches to studying the Soleure Jura, Gressly developed fundamental principles that guide our science today.

Establishing the Concept of Facies

Teichert (1958) summarized Gressly's use of the term "facies" and his derivation of the facies concept, and translated relevant passages into English. We extend this process because Gressly's purpose was not just to propose the term "facies" for descriptive rock attributes independent of time connotation. Rather, Gressly recognized it was essential to distinguish a rock term ("facies") from a time term ("terrain" or time-stratigraphic unit). Without having a language to express these two properties of strata, one cannot differentiate between lateral variations in lithology ("facies") along one or more beds [time-stratigraphic units], and vertical changes and repetitions in lithology through a succession of beds.

To recapitulate the thread of observations and logic which Gressly followed, we begin with his understanding of facies. As illustrated by the example below, Gressly discovered through detailed field work in the Jura that rock types ("facies") and their fossil constituents change in regular order along beds and in vertical succession from one stratigraphic unit to another.

> "The coral facies comprises several subfacies, which vary in the different stratigraphic units [stratigraphically] and regions [geographically] of our Jura, and which are useful to know in order to understand the laws of distributions of paleontological associations. These subfacies are explained as transitions which link the major facies, and allow appreciation of the slightest nuances in the living conditions of the organic world now buried in the earth's crust. Thus coquinas link petrographically the purely coral facies to the purely muddy facies, passing through the ooliths and pisoliths, to the sandy and gravely varieties (mixtures) of the muddy

> facies. Analogous passages from one paleontological assemblage to another always accompany these petrographic transitions." 15/27-16/6.

> "Using this observation, I have managed several times to follow [along a bed] the increase of debris size [of skeletal fragments] and preservation to find the original habitat. There, one finds the fossils in place, with a prodigious profusion and so well conserved that one can study the most minute details of the organization and characteristic assemblage, the behavior and habits, as we will see in the following descriptions of terrains." 16/l6-26

Gressly applied the term "facies" to signify those observable physical, chemical and biological properties of rocks which collectively permit objective description as well as distinctions among rocks of different types. Gressly explicitly discriminated between objectively observable properties and any connotation of their age. It is apparent that he considered it necessary to make such a clear distinction, because he abandoned the historical Wernerian term "formation" after the first two pages of his publication, and subsequently used "facies" for a descriptive rock term and "terrain" for a time-stratigraphic unit that contained variable rock types.

> "In this way, I have come to understand that within the areal extent ["dimension horizontale"] of each stratigraphic unit there are several well-defined variables which show the same features in petrographic composition as well as in the paleontologic attributes of their fossil content, and which are governed by specific and fairly constant laws." 10/30-11/3

> "Above all, there are two major facts which define everywhere the sum of the variables which I call *facies* or the *aspects of a stratigraphic unit*: one is that within a stratigraphic unit the occurrence of a specific lithology necessarily also requires the occurrence of a specific paleontological association; and the other is that a given paleontological association rigorously excludes those genera and species of fossils which are frequent in other facies." 11/4-10

Gressly provides some clues about the origin of his understanding that facies change along beds, and that the laterally adjacent facies are time equivalent. In the monograph which follows the text we have translated, he describes different uses of the rock varieties which compose the Corallian terrain. Architectural uses of the different rock varieties are dependent on the natural dimensions of quarried rock produced by bedding, and on rock strength. He notes that whereas quarries near the massive coral bioherm provide large, equidimensional blocks used for wall construction, quarries farther from the center, in the same bed, provide thinner slabs of homogeneous limestones used for posts, lintels and sills. Quarries from the bioherm center (brecciated beds of the Corallian terrain) provide a chalky white stone rich in fossil fragments already used by the Romans for architectural ornaments and sculpture. Other uses of stone from the Corralian terrain include limestone specially suited for mortar, and limestone suited for use as a flux in window-glass making. Gressly obtained his knowledge about these multiple uses of Jura limestones as a youth. He lived with his family in the glass factory, which was owned by the more prosperous side of the Gressys and which employed his father. He was familiar with the different applications of limestones of varying characteristics obtained from the numerous small quarries excavated into a conspicuous single flat lying coral bed near his hometown. He had only to relate the different physical and chemical properties important for industrial application to the distribution of particular paleontological and sedimentary attributes of facies.

Establishing the Relationships between Depositional Environments and Facies Distributions

Having explained that facies are properties of rocks not specific to time, Gressly further recognizes that facies are products of genetic processes that operated in the depositional environments in which they accumulated. Just as laterally linked depositional environments change over a geographic area, the facies which are incorporated into the stratigraphic record change gradationally along beds which parallel original depositional surfaces. He observes that by walking along beds and following changes in the physical and biological [fossil] components of facies, one can establish the details of a depositional profile.

> "I think that the petrographic or paleontological changes of a stratigraphic unit in the horizontal are caused by the changes in environment and other circumstances, which still so powerfully influence today the different genera and species which inhabit the ocean and the seas. At least, I often have been astonished to find in the distribution of our fossils the laws of living communities and in the corresponding assemblages of petrographic and geognostic characteristics which correspond to the living communities, the environmental conditions which rule in the submarine world." 12/4-12

Gressly not only understood the connections among facies, their genetic relation to depositional environments and consequent lateral facies transitions along paleodepositional profiles, but he observed regular order in lateral and vertical successions of facies. When he followed the beds laterally, he always found the same lateral succession of petrographical and paleontological attributes. Gressly understood that he was walking along depositional (time) surfaces as he walked along single beds. We have previously given citations from Gressly (15/27-16/6; 16/16-26) in which he discusses transitional facies between end-members, gradual decrease in skeletal size within a bed away from the source of the skeletal debris, and the association of specific fossil assemblages with specific facies.

Gressly also observed that biological [fossil] variations occur in consort with the physical attributes in both end-member and transitional facies. He regarded these variations as reflections of the physical environment and the characteristics of habitats. He explained that if individuals of a species occur outside their usual facies, they are more rare and morphologically atypical than when found in their typical facies. He also recognizes that generalist species occupy or dominate transitional facies, but specialist species dominate in the typical (end member) facies settings.

> "In the meantime, it is perhaps not out-of-place to briefly comment on my present way of understanding the correlations between the geognostic constitutions of stratigraphic units [the attributes allowing geological interpretation] and the fossil assemblages they contain." 12/29-31

> "These two end member rock types, either pure or mixed, constitute facies well defined by their petrographic characteristics, which vary according to their littoral or pelagic depositional environments. Their paleontological features are no less distinctive and always correspond even in the slightest detail to the geognostical [structure, bedding and stratification] and petrographic features, as we will see in what follows in treating each stratigraphic unit in detail. I will only show here the major facies which are constant throughout all our stratigraphic units as far as I know their extent through my own observations, all the more so in that the more or less numerous local and transitional subfacies can easily be linked to the major facies." 13/11-21.

> "If, by chance, certain genera and species which characterize a specific facies are found in another facies, it is a general rule that specimens of these genera and species will be much rarer, less developed and less characteristic than in the facies or general assemblage to which they normally belong. Similarly, wherever the geognostic characteristics of a facies [indicators of inferred depositional processes or environments] are best developed, the paleontological assemblages also are the best expressed, the genera and species are most numerous and individuals are most typical, best developed, and are commonly in a perfect state of preservation. If the facies show intermediate characteristics with mixed geognostic features, the fossils also share less typical attributes. In this case they are generally rare, poorly preserved, poorly developed and belong to few genera and species; however, there are occasional well-formed fossils which belong mostly to different species than those in the principal facies or which rarely occur in them." 11/11-26

Gressly recognized that fossil morphologies reflect the physical and chemical attributes of their habitat, and regarded the fossil composition as informative and important to environmental interpretation as the physical facies attributes. He used several pages describing parallel changes in fossil morphology and physical facies for reef and contiguous shelf habitats, and demonstrating intermediate or transitional forms of each.

> "Breccias, coquina, oolites, pisolites, mostly coarse grained, constitute the coral facies and associated deposits such as reworked sediment and immediate transitions to muddy facies. These rocks always show the characteristics of littoral and shallow marine deposits and only contain fossil assemblages which are characteristics of coral beds, mainly composed of fixed massive or branching corals, which resists the shock of waves and which living genera and species such as the *Agaricias*, *Astreas*, *Oculinas*, *Caryophyllas*, etc., today build coral banks and reefs in tropical seas that are so dangerous to ships. These corals always are accompanied by other organisms common to coral reefs, which appear to flourish in high energy, agitated water, thus always giving a morphology that provides resistance to the waves, the ones being firmly fixed to the substrate, the others having an extremely elastic structure which gives and bends in the

force of the waves but recovers instantaneously, and comes out victorious from the incessant combat. The external morphology of the organisms and the layout of their organs are no less appropriate to the circumstances which govern their existence. Commonly all these properties are united to reach the objective." 13/22-14/10

In other examples he compares fossil morphologies in different habitats. He relates the assemblage of species (communities) in these habitats to morphologic adaptation to the physical and chemical conditions of the respective environments. In the case of muddy habitats cited below, he observes that genera and species of the faunal assemblages have thin, smooth, less ornate shells which are not resistant to transport.

"A general trait, which is constant for all paleontological assemblages of the muddy facies, is that the dominant genera and species have tests less apt to resist destructive effects of reworking. The shells, among others, are normally very thin, very much smoother, less ornate, less ornamented with different protuberances than in the preceding (coral) facies where they have a very pronounced massive resistant character. However, there are sometimes genera and species with very thick shells but which have a less robust structure and which easily delaminate and disaggregate by abrasion." 18/4-13

In several places he develops and illustrates niche-specific morphologic adaptations of species to their habitats, as illustrated by the following example.

"One very important characteristic which is universal to organisms within the coral facies is a very thick shell, always highly ornamented by ribs, striations, spines, nodes, and other ornamentation giving a strange, very particular physionomy, very irregular and useful for determining the niches they occupy in an ocean long gone from the surface of the earth." 15/20-26

Establishing the Concepts of Vertical Facies Successions and Laws Governing Lateral and Vertical Distributions of Facies

Having established the genetic relation between facies and depositional environments, and having equated the lateral variability of facies along beds of the same age with the mosaic of depositional environments along depositional profiles, Gressly considered the dynamics of the geomorphic process-response system through time and extended these relations into the four-dimensions of stratigraphy. He established that the regular patterns and trends of facies observed laterally along beds were replicated through a vertical succession of beds. Moreover, the vertical succession of facies through a series of superposed beds was repeated within larger scale stratigraphic units. The regular vertical succession of facies was accompanied by a regular succession of fossils. He explained these similar vertical and lateral arrangements of facies and the controls of their distribution in the form of five laws.

"After having determined the major facies which dominate our Jurassic terrains, it remains to take a look at the laws which underlie and control their distribution both vertically and horizontally." 20/22-25

Gressly's first law that facies change transitionally within coeval beds is:

"*Each facies of a stratigraphic unit has its own distinctive petrographic and geognostic or paleontologic attributes which do not represent the characteristics of the entire stratigraphic unit, nor the attributes of the other facies forming the same geological level* [stratigraphic interval]." 20/28-32 [italics from Gressly]

This understanding of lateral facies transitions within time-stratigraphic units given by the first law is the basis for correlation and stratigraphic interpretation of lateral and temporal equivalency of rock bodies, as expanded upon by his paragraph following the first law.

"This law will help correct the classifications of many stratigraphic units and their subdivisions by defining more precisely their position (stratigraphically and geographically), and will therefore avoid the serious mistakes in determining the geological level of localities (correlation of stratigraphic intervals) which are separated by large rock bodies with different characteristics." 21/1-4

Gressly's second law that fossils share morphologic attributes related to the rock types (environments) in which they occur, regardless of age, is:

"*Facies having the same petrographic and geognostic attributes show extremely similar paleontological characteristics throughout the stratigraphic succession* ["terrains"], *and occur in similar sequence through a varible number of superposed stratigraphic units*." 21/6-9 [italics from Gressly]

After stating his second law, Gressly develops at length its significance to paleontology and biostratigraphy. He notes that facies of similar lithologic and sedimentologic characteristics contain fossil assemblages which are analogous in terms of gross morphology, but the fossils are different in detailed anatomy. He attributes this observation to the general control of the habitat on morphology, whereas anatomical details change from one stratigraphic unit to another reflecting time dependency. In summary, because similar facies are deposited in similar environments of different ages, and since the external morphology of fossils is related to habitat, fossils in similar facies will look alike regardless of age. But, subtle variations in morphology are related to age (now, evolution).

Gressly's third and fourth laws and accompanying discussions concern the lateral and vertical distributions of facies. The third law expressses the nature of lateral transitions, whether abrupt or gradational, from one facies to another. The fourth law expresses regular, unidirectional increases or decreases in diversity of facies as one passes along a bed or through a succession of beds. The third law is somewhat ambiguous as to whether it refers only to lateral facies transitions along beds or to both lateral transitions and vertical facies successions through beds. The accompanying discussions imply that Gressly is aware that both abrupt and gradual facies transitions occur vertically through a succession of beds and laterally along a bed. He recognized the difference between normal stratigraphic successions and geographic dislocation or offset of facies tracts. We consider his following statement as support for this opinion.

> "Moreover, in some cases, following a considerable (thick and laterally extensive) pelagic deposit, littoral facies appear abruptly, almost without any gradual transition. This phenomenon, although infrequent, once again begins at the Lower Oolite. It coincides with the abrupt or gradual horizontal facies transitions of the stratigraphic units which I pointed out previously." 23/1-6

Gressly's third law is:

> "*Sometimes lateral ["horizontal"] facies transitions are abrupt, sometimes the transitions are gradual and one facies passes into another through intermediate varieties whose transitional features are poorly expressed, which together with the mixing of end-member facies, makes it difficult to separate them.*" 22/9-13 [italics from Gressly]

Gressly's fourth law is:

> *"Diversity of the facies increases in a vertical direction from base to top throughout the whole series* (stratigraphic succession through the Jurassic) *and, conversely, diminishes gradually in the opposite direction."* 22/24-26 [italics from Gressly]

Gressly's laws are distilled from discussions and commentaries about facies and stratigraphic relationships he had observed in the Jura. Some of Gressly's commentaries relevant to the third and fourth laws include the following ideas. He recognizes facies substitutions and explains that coral boundstones and lagoonal mudstones may substitute for each other in vertical successions and lateral transitions because they occupy similar water depth ranges. He describes facies offsets or stratigraphic discontinuities between successive beds in contrast to normal regular vertical facies successions. These stratigraphic discontinuities are created by major lateral shifts in facies at specific stratigraphic positions. Last, Gressly observes that abrupt or gradual facies transitions occur laterally along beds and vertically through a series of beds, thus demonstrating the lateral and vertical equivalency of facies relationships which has become known as Walther's Law.

> "The coral facies comprises several subfacies, which vary in the different stratigraphic units and regions of our Jura, and which are useful to know in order to understand the laws of distributions of paleontological associations. These subfacies are explained as transitions which link the major facies, and allow appreciation of the slightest nuances in the living conditions of the organic world now buried in the earth's crust. Thus coquinas link petrographically the purely coral facies to the purely muddy facies, passing through the ooliths and pisoliths, to the sandy and gravely varieties [mixtures] of the muddy facies. Analogous passages from one paleontological assemblage to another always accompany these petrographic transitions. It is always the most delicate forms which dominate in the transition zones." 15/27-16/7.

> "What I have said about vertical succession of facies is not without exception, and it is obviously natural that this law should vary according to the petrographic aspects and geognostics of rocks and stratigraphic units. We should thus not be surprised to find within a muddy rock, above or below

> a coralline rock, fossils which live in mud. But these fossils of the muddy facies will indicate no less than the corals a shallow marine or littoral environment even though these rocks are of a different type according to their depositional process." 21/31-22/6

> "Abrupt facies transitions are particularly obvious between coral dominated facies and pure muds, above all when the coral beds are surrounded by subpelagic [transitional between pelagic and littoral] or pelagic deposits. In other cases this transition is more gradual and much less perceptible. This happens particularly between coral and muddy littoral facies which are commonly interspersed, as if their characteristics radiated from the centers or nuclei of rich organic growth out to the periphery which only shows broken debris or a few undifferentiated or poorly developed fossils." 22/14-23

> "Moreover, in some cases, following a considerable [thick and laterally extensive] pelagic deposit, littoral facies appear abruptly, almost without any gradual transition. This phenomenon, although infrequent, once again begins at the Lower Oolite. It coincides with the abrupt or gradual horizontal facies transitions of the stratigraphic units which I pointed out previously." 23/1-6

With his fifth law, Gressly applies the other four laws to reconstruct paleogeographies through time. For successive time intervals he distinguishes three facies tracts ("zone" and "band"): littoral, pelagic and subpelagic. He mapped these over a wide area from the Vosges and Black Forest in the north (along the Rhine north of Basel, Switzerland), through the Neuchatel Jura, to the Savoy subalpine area in the south. He recognizes that facies diversity increases regularly across this region from the pelagic facies tracts in the south, through the subpelagic, into the littoral facies tract in the north. He established that these facies tracts maintained approximately constant geographic positions and widths throughout the Jurassic. The fifth law is stated as "*The diversity of facies is more or less constant in different regions*[facies tracts]."

> "One could draw a line starting from Randen… as far as Chatelu…, running parallel to the foot of the Black Forest and the Vosges which would divide the littoral facies and the pelagic facies almost exactly into two separate parallel Jurassic zones. The western… swath continues toward… where it loses part of its characteristics and only constitutes a very thin, irregular boundary between the pelagic deposits and the large Jurassic bay… which is almost entirely filled by littoral deposits which gradually thin from the Swiss border to the foot of the Vosges, showing paleontological characteristics which are increasingly littoral in all the terrains." 23/14-30

> "The other zone which is pelagic, begins in Argovia and forms a less broad swath comprising the ranges of the Soleure and Bernese Jura which lie on the edge of the Swiss basin and the Tertiary valleys which run in to it. This swath is broader in the Canton of Neuchatel and would seem to comprise the whole of the Vaud and Geneva Jura…" 23/31-24/5

> "The subpelagic facies tract is intermediate between the littoral and pelagic facies tracts, and forms a transition zone more or less closely linking them. In the Canton of Schaffhouse and in Argovia this facies tract predominates with respect to the others, sometimes being more littoral sometimes being more pelagic, going from the Portlandian to the lower oolite through the Coralline Terrain and the two stratigraphic units of the Oxfordian." 24/6-11

Establishing the Foundation of Walther's Law

Gressly's statement that abrupt or gradual facies transitions occur in the same order laterally along beds and vertically through a series of beds (quoted previously; 23/1-6) is a description of relations among depositional environments, their distribution along a depositional profile and stratigraphy resulting from progradation, which later became known as Walther's Law of the Correlation of Facies. In another part of the paper, Gressly further develops the idea of the equivalency between the lateral distribution of facies along a bed (depositional profile) and the vertical succession of facies through a series of beds. A less literal but more easily understood translation of lines 11/27-12/3 than that given in the Appendix reads as follows.

> The subtle variations in faunal assemblages (related to lateral facies transitions) play an analogous role within each small-scale time-stratigraphic unit (albeit on a vastly different scale) to that played by fossils of genuine stratigraphic value (such as the knotty ammonite, the arcuate Gryphea, the Baculites) vertically within the larger-scale lithostratigraphic units. 11/27-12/3

Thus, not only did Gressly understand that the lateral succession of facies along a depositional profile was repeated vertically through a series of beds, but he understood that fossils had two fundamental usages. First, some fossil groups reflect the environments in which they live and some fossils are particularly useful in paleoenvironmental interpretation. Second, other fossil groups occur in specific, limited stratigraphic intervals and therefore are particularly useful for biostratigraphic correlation.

Gressly's observations about the vertical and lateral relationships of facies were almost immediately adopted and exploited, culminating in Walther's (1894) reexplanation of the relationships and his discussion about how that information could be applied in stratigraphic correlation. By contrast, as noted by Teichert (1958), Gressly's observations about the two usages of fossils were not incorporated into common practice. Gressly's contemporaries focused on the facies and paleoenvironmental applications of fossils, and a more precise development of biostratigraphic applications did not occur until Oppel in the 1850s.

Gressly stressed the value and application of paleontology in both contexts for two reasons. First, he wrote that a purely physical and mineralogical approach toward the study of sedimentary rocks, in the absence of paleontological information, was a sterile science. Second, he felt that a balanced physical and biological approach added important and corroborating information which made interpretations more robust. After Oppel, until the end of the century, biostratigraphic applications dominated stratigraphy. In response, Walther (1894) had an analogous reaction as Gressly. He lashed out against the imbalanced use of fossils only for biostratigraphic applications, just as Gressly had rejected the imbalanced, solely mineralogical approach to the study of strata in his time. Walther insisted on applying detailed information about the physical aspects of strata, expanding and emphasizing the principles first enunciated by Gressly.

Consolidating an Approach to Stratigraphic Analysis

Gressly concludes the first part of his paper by presenting the advantages of his stratigraphic approach in four points.

1. It simplifies the apparent complexity in paleontology and provides a coherent link between paleontological and physical/lithological attributes by establishing a limited number of closely interrelated laws.
2. It explains the physical attributes of sedimentary rocks, "making them useful to science by carrying them from the realm of sterile [purely descriptive] mineralogy to the realm of geology by showing their relationships with the progressive development of life as is manifest at the different epochs of the history of our planet. [evolution]"
3. It is the basis for reconstructing successive paleogeographies and depositional profiles through time.
4. It is the basis for reconstructing the times of deformation using unconformities overlain by littoral deposits.

Surprisingly, Gressly omitted from this list one of the most important advantages, the one which resulted from his initial questioning of the Neptunist paradigm that his work helped discard. He developed a new method of stratigraphic correlation, based not upon establishing the equivalency of rock type, but upon establishing equivalency of rocks in a time frame. So, we add to Gressly's four, a fifth advantage to his approach to stratigraphic analysis; it is the basis for understanding four-dimensional time-stratigraphic relationships. He understood that there are two basic concepts in stratigraphy: the first is that sediments accumulate by a set of processes in depositional environments; and the second is that this happens during the passage of time. Because he separated the temporal and physical attributes of rocks in such a clear way—and defined corresponding terms to express this distinction—he established a novel approach to stratigraphic correlation that is valid to this day.

Firming-Up the New Paradigm

Gressly established the following stratigraphic concepts: (1) sedimentary facies record the processes and conditions of the environment in which they accumulated, and are interpreted by analogy with modern environments; (2) several facies coexist at the same water depth and may therefore substitute for each other as sediment accumulates through time; (3) the morphologies of fossil species reflect the physical and chemical conditions of their habitat, but nuances in their morphologies reflect evolution; (4) certain fossils are more useful for interpreting the environment of deposition ("facies fossils"), whereas others are more useful for establishing the age of a stratigraphic unit ("index" or "zone" fossils); (5) time-stratigraphic surfaces are defined by beds which follow a depositional profile; (6) facies change transitionally in a unidirectional trend along depositional profiles, and this trend is repeated in vertical sequence through a succession of beds (a working description of Walther's Law); (7) stratigraphic correlations based upon lithologic equivalency are demonstrated to be invalid for the area he studied (and by extrapolation, this applies to all cases); (8) stratigraphic correlations must be based upon the time equivalency of stratigraphic units, even if their facies differ; (9) the depositional profiles and regional facies trends within a limited stratigraphic interval define the regional paleogeography.

After Gressly's contributions had been absorbed into common practice, the addition of a few new concepts was necessary to complete the current stratigraphic paradigm initiated by Gressly. These additional concepts were: (a) the stratigraphic process-response system conserves mass (and by implication the conservation laws apply to stratigraphy); (b) sediment volumes are differentially partitioned into facies tracts within a space-time continuum as a consequence of mass conservation; (c) cycles of facies tract movements laterally (uphill and downhill) across the earth's surface are directly linked to vertical facies successions, and are the basis for high-resolution correlation of stratigraphic cycles; (d) stratigraphic base level is the clock of geologic time, and the reference frame for relating the energy of space formation with the energy of sediment transfer; and (e) facies differentiation is a byproduct of sediment volume partitioning.

Conservation Laws Apply to Stratigraphy

The first additional concept to the current stratigraphic paradigm was contributed by Johannes Walther (1894). He expressed a fundamental requirement of stratigraphy, that the stratigraphic process/response system must conserve mass.

His understanding of this concept is explained in the simple observation that a succession of strata at one place is equivalent in time to a stratigraphic surface of discontinuity at another place. That is, if erosion is occurring in one zone along a geomorphic profile, sediment must be accumulating elsewhere. Through this expression, he accounts for the existence of unconformities and condensed sections at certain geographic positions which formed at the time when sediments were accumulating at other geographic locations. Walther further stated (p. 996) that "It is clear indeed, that no material can disappear from the earth, that the mass of earth material remains constant (if we disregard falling meteorites)." This mass balance requirement, although essential to stratigraphic understanding, is not commonly stated explicitly or used implicitly today.

Walther's understanding of mass conservation requirements was enunciated even more clearly and specifically a few years later by Barrell (1917); "A disconformity marks a period of time which is represented in some other region by a deposit of formation [rock] value." It is revealing that from the start stratigraphic process-response systems were considered in the same context as other physical and chemical systems and regarded as operating with the same basic laws.

Sediment Volume Partitioning

Recognition of mass conservation in the stratigraphic process/response system led to the corollary concept of sediment volume partitioning by Barrell (1912). Walther had recognized that there was severe time-space partitioning of sediment at times when erosional unconformities and surfaces of sediment starvation formed. But Barrell extended this concept to include time-space variations in volumes of sediment accumulated in different facies tracts even when unconformities or surfaces of sediment starvation were absent.

Barrell illustrated the concept of sediment volume partitioning with a delta example. He showed that facies tracts moved uphill and downhill, and that the widths and thicknesses of these facies tracts increased and decreased in regular progressions. Barrell thought these changes occurred in response to sea-level variations and uphill and downhill movements of sites of sediment accommodation. This principle has been applied in stratigraphic interpretation of seismic data during the last two decades, largely due to the popularity of seismic and sequence stratigraphy initiated by P.R. Vail's group in EXXON (Payton, 1977).

Cycles of Facies Tract Movements are Equivalent to Stratigraphic Cycles Defined by Vertical Successions of Facies

Walther is better known today for his "Law of the Correlation of Facies" than he is for expressing the requirement that mass is conserved in stratigraphic process-response systems. This is largely due to G.V. Middleton's (1973) account of Walther's work. Middleton focused on Walther's understanding of the relationships between vertical facies successions and lateral facies transitions which are required geometrically by sediment accumulation on an inclined surface, i.e., progradation. However, Middleton did not dwell on the importance of those relationships in the context of stratigraphic correlation, even though it was within this stratigraphic context that Walther constructed his law, as was emphasized by his title. To understand Walther's insistence about the need to formulate such a law for the purpose of stratigraphic correlation, we may view his insight from a historical context.

Walther first restated Gressly's observation that the descriptive, physical attributes of a rock (Gressly's "facies") reflect the processes which operated in the environment where the sediment accumulated. Walther wrote (1894, p. 977), "When we examine the primary qualities of the rocks, we cannot help but notice that in many ways they are strongly dependent on external conditions.… But there is not only a causal relationship between the single deposit and the climatic conditions under which it arose, but also the several types of structures of one and the same facies tract are most closely connected by means of the same or similar circumstances of formation." Walther recognized that similar environments have similar processes, and will therefore produce similar sedimentologic products.

Like Gressly, Walther distinguishes between the genetic origin (process-response) of rocks (Gressly's "facies") and their time value (Gressly's "terrain"), and he cautions several times that these two aspects of rocks must not be confused. He notes that "If we seriously want to pursue the history of the earth, …" (to Walther, this is the primary objective of geological study), "then we have to establish the ages of rock units independent of lithology so that successive paleogeographies can be reconstructed."

He asserts that fossils alone are an inadequate means of establishing stratigraphic correlations, and that correlation based upon physical attributes of strata is essential (p. 979); "The simplest consideration will teach that this task [stratigraphic correlation] cannot be fulfilled with the help of organic remains and on the basis of characteristic fossils.… Here paleontology alone can do nothing and needs the help and support of other methods. We believe that comparative lithology can remove these same difficulties which comparative anatomy has discharged for the field of paleontology." And he writes (p. 981) "…there are no zone fossils that can tell us which rocks are to be seen as heteropic, simultaneous deposits of the whole earth surface.… The geologist finds himself in the fatal situation of being unable to recognize different formations either as contemporaneous or as belonging to different ages with certainty.… only the ontological method can save us from [bio]stratigraphy, and only the laws of the correlation of facies are in the position to widen our knowledge." Finally, he notes that even unconformities and other surfaces of stratigraphic discontinuity only help establish relative ages of rock units rather than true temporal equivalency of correlation (p. 983); "… but when a transgression results from a positive shoreline shifting, the single discordance cannot possibly be of the same age, and the 'relative same age' is encountered rather lamely again."

With these arguments Walther establishes the need for a method of temporal correlation of strata independent of biostratigraphy. In reaction to what he considered an excessive emphasis of using fossil data exclusively as the basis for establishing temporal relations of strata, Walther focuses on physical attributes of strata for correlation. He even states that the primary purpose of his book is to describe a method of stratigraphic correlation based upon the concept of equivalency between lateral facies transitions and vertical facies successions (p. 984); "However, our opinion offers a means through the correlation of facies to change the homotaxy [relative age equivalency] of the characteristic fossils into a homochrony [equivalent age] of the rocks. We have described this way briefly in the section before, and this entire work is a guidebook for the new way."

It is in this explicit context of needing a method of correlation that the "Law of the Correlation of Facies" is expressed. Walther adopted Gressly's Facies Laws which establish that facies transitions along depositional profiles are repeated in vertical facies successions. He recognized that progradation resulted from accumulation of sediment along the inclined surface of a depositional profile, and provided a hypothetical example of sediment filling a fjord during a period of unchanging sea level. He understood that a necessary geometric consequence of progradation is the downhill (or seaward) translation of uphill (or landward) facies tracts, resulting in a downhill-to-uphill (or deep-to-shallow) vertical succession of facies. Because environments are laterally linked along a depositional profile, the downhill and uphill translations of environments are recorded simultaneously at all positions along a depositional profile. Vertical facies successions at all positions within a stratigraphic unit record these simultaneous translations of environments and are the basis for stratigraphic correlation. This explicit linkage between the "zig zag" up- and down-hill movement of environments and the expression of these movements in vertical facies successions as stratigraphic cycles is the insight Walther added to the lateral and vertical relationships that previously had been described by Gressly and which are now called "Walther's Law."

Stratigraphic Base Level is a Reference Frame for the Passage of Time and the Sites of Sediment Accumulation, Erosion and Nondeposition

The initial step toward the next fundamental new stratigraphic concept was Barrell's (1917) recognition that stratigraphic successions record transits of base level up and down across the earth's surface. Where base level is above the earth's surface, sediment will accumulate if sediment is available. Where base level is below the earth's surface, sediment is eroded and transferred downhill to the next site where base level is above the earth's surface. These transits of base level up and down across the earth's surface produce a stratigraphic record at a fixed geographic position of alternating episodes of deposition and erosion seen as regular vertical successions of facies separated by surfaces of unconformity. The up and down movements of base level coincide with the uphill and downhill "zig zag" movements of facies tracts and the concomitant cycles of vertical facies successions recognized by Gressly and Walther.

Of course, we now realize that base-level movements do not involve transits across the earth's surface at all geographic locations. In some places, at some times, base level oscillates up and down entirely below or entirely above the earth's surface. Where base-level oscillations are always above the earth's surface, sediments may accumulate at increasing and decreasing rates, and these cycles are recognizable in conformable strata.

The critical issue is that Barrell recognized the metronome aspect of base-level cycling, and understood that the stratigraphic cycles produced by the uphill and downhill movements of facies tracts during base-level cycles were the basis for high-resolution stratigraphic correlation. He also understood that time was continuous and that time is fully represented in the stratigraphic record by the combination of rocks plus surfaces of stratigraphic discontinuity. The time represented by an unconformity at one geographic position is represented by rock at another position.

The next insight which completed the fundamental principle that stratigraphic base level is the reference frame for the passage of time and the accumulation of sediment was contributed by H.E. Wheeler in 1964. During the intervening half-century, the term base level was used in numerous, contradictory ways, but primarily in geomorphic rather than stratigraphic contexts. Barrell's notion that strata are naturally divisible into stratigraphic cycles that record the rise and fall of base level at multiple frequencies went unchallenged, unmodified and unused. Wheeler brought the term back to stratigraphy and introduced a different notion of base level that was more appropriate for stratigraphic analysis.

Wheeler considered stratigraphic base level as an abstract (nonphysical), nonhorizontal, undulatory, continuous surface that rises and falls with respect to the earth's surface. As base level rises, intersections of the base-level surface and the seaward-inclined earth's surface move uphill. This increases the area of the earth's surface below base level where sediment may accumulate, and increases the sediment storage capacity in continental environments. As base level falls, the opposite occurs. Stratigraphic base level is a descriptor of the interactions between processes that create and remove accommodation space, and surficial processes that bring sediment to or that remove sediment from that space. In effect, but not explicitly, Wheeler defined stratigraphic base level as a potentiometric energy surface that describes the energy required to move the earth's surface up or down to a position where gradients, sediment supply, and accommodation are in equilibrium (Cross *et al.*, 1993).

Wheeler's stratigraphic base level is the conceptual device that links several concepts: Gressly's facies and facies tracts; Walther's notion of the "zig zag" uphill and downhill movement of facies tracts; Gressly's and Walther's identification that this movement is recorded as regular vertical facies successions that define stratigraphic cycles; Barrell's notion that base-level cycles are the clock of stratigraphy (and therefore that correlations based upon physical stratigraphy are possible); and the concept of sediment volume partitioning.

Facies Differentiation is a Product of Sediment Volume Partitioning

The last fundamental principle to be emplaced within the current stratigraphic paradigm is the concept of facies differentiation (Van Siclen, 1958; see summary in Cross, et al., 1993). This principle has been slow to develop and become recognized and applied in stratigraphic analysis. But, with the hindsight of history, we can see hints of its recognition and usage during the past half-century, particularly in Wilson (1967), Curtis (1970), MacKenzie (1972), Wilkinson (1975), Galloway (1986), and Sonnenfeld and Cross (1993).

Accompanying sediment volume partitioning are differences in stratal geometries, facies associations and successions, lithologic diversity, stratification types, and petrophysical attributes of strata which are preserved within identical facies tracts but in different portions of base-level cycles. The term *facies differentiation* refers to these changes in sedimentological and stratigraphic attributes during base-level cycles. Facies differentiation reflects the degree of preservation of original geomorphic elements, as well as the variations in types of geomorphic elements that existed within a depositional environment at different times.

There are two principal categories of facies differentiation. The first encompasses the changes in attributes of a single facies that occur during base-level cycles. The deposits of a braided stream that accumulate during low accommodation, for example, have limited facies diversity. By contrast, the deposits of a braided stream that accumulate during high accommodation have increased facies diversity. In the latter case a greater variety and a larger proportion of the original geomorphic elements of the braided stream are preserved, although the geomorphic elements of the braided streams were the same in both cases.

The second type of facies differentiation is a complete change in the types of facies and/or the facies successions that occur at the same position along a topographic profile of deposition. These changes in facies assemblages reflect changes in the geomorphic constituents of the depositional environment. A common example is the alternation of wave-dominated, open-ocean-facing shorefaces during base-level fall, with tidal current dominated open bay, gulf and estuary environments during base-level rise. The geomorphic elements occur alternately at the same position along the topographic depositional profile and at the same range in water depths. Essentially, the open-ocean facing, wave-dominated straight coastline is temporarily replaced during times of base level rise and increasing accommodation by an embayed coastline where wave energy is dampened and tidal currents are enhanced.

The degree of preservation is a consequence of the ratio of accommodation to sediment supply. Sediment volumes and geomorphic elements are more completely preserved during base-level rise when accommodation space is increasing, than during base-level fall when accommodation space is decreasing. Consequently, there are specific and distinctive stratigraphic signatures of the different parts of base-level cycles. The sedimentologic and stratigraphic attributes of facies tracts commonly described in "facies models" and "depositional system models" are thus mixtures of attributes which existed separately during base-level cycles.

The Origin of Gressly's Ideas and Some Unanswered Questions

Although biographies document Gressly's life (e.g., Stampfli, 1986, and references cited therein), there remains considerable mystery about several aspects of his intellectual leaps toward establishing a new philosophical approach and methodology of stratigraphy. Was the concept that a facies represents the products of processes operating in specific environments passed along to Gressly (perhaps by Voltz; Gall, 1976), or did he discover it through personal observations of strata in the Solothurn Jura? If Gressly discovered the significance of relating observed lithologic attributes to the processes that formed them, then how did he understand that association since he had no first-hand knowledge of a marine environment or modern marine sediments until 1859? Did his understanding of marine carbonate paleoenvironments come from literature, such as Charles Lyell's Principles of Geology, or from his mentors and friends? Why did Gressly not publish on facies and stratigraphic correlation after his first and only paper on the subject? These questions are unanswered despite considerable bibliographic and historical research, some of which is cited above. Perhaps additional knowledge can be gleaned from study of his field notes and unpublished manuscripts that are stored in the Solothurn museum.

A Lesson from Gressly's Approach

A common perception in the practice of sedimentary geology today is that variations in stratigraphic architecture, facies compositions and assemblages, and petrophysical attributes of sedimentary rocks are complex, disorganized, highly variable and haphazard "noise" of the stratigraphic record. But, however great the complexity and variability in sedimentologic details, this perceived "noise" must originate from the preservation of varying proportions of original geomorphic elements as strata. We are confronted today with a similar problem to the one which Gressly solved by carefully documenting all those attributes which he could master with the means available at his time.

Using Gressly's approach, this "noise" would be considered to have a high information content and a regular, predictable structure. Quantitative measurements of sedimentological, biological and petrophysical attributes should provide information crucial to unravelling the complex history of sedimentation. Examples of sedimentological attributes to measure include bedset thickness of identical types of cross stratification; bedform diversity; frequency of shale partings; frequency and amount of relief on scour surfaces; and degree of preservation of original geomorphic elements. Examples of biological attributes include microfacies composition; faunal size; species diversity; number of trophic levels; and reproductive strategy of populations. Examples of petrophysical attributes include porosity, permeability and capillary entry pressure. Recording of these attributes within a time frame given by the changes in accommodation should provide a clearer and coherent picture of the details of stratigraphy.

Conclusions

Amanz Gressly began geological field studies in the Jura Mountains with the intention of mapping and correlating strata, and reconstructing successive paleogeographies within the existing paradigm of Wernerian Neptunism. His careful observations caused him to recognize the invalidity of the tenets of that paradigm, which he jettisoned, and he developed the foundation of the stratigraphic paradigm we have today.

Gressly established the following stratigraphic principles: (1) sedimentary facies record the processes and conditions of the environment in which they accumulated, and are interpreted by analogy with modern environments; (2) several facies coexist at the same water depth and may therefore substitute for each other as sediment accumulates through time; (3) the morphologies of fossil species reflect the physical and chemical conditions of their habitat, but nuances in their morphologies reflect evolution; (4) certain fossils are more useful for interpreting the environment of deposition ("facies fossils"), whereas others are more useful for establishing the age of a stratigraphic unit ("index" or "zone" fossils); (5) time-stratigraphic surfaces are defined by beds which follow a depositional profile; (6) facies change transitionally in a unidirectional trend along depositional profiles, and this trend is repeated in vertical sequence through a succession of beds (a working description of Walther's Law); (7) stratigraphic correlations based upon lithologic equivalency are demonstrated invalid for the area he studied (and by extrapolation, this applies to all cases); (8) stratigraphic correlations must be based upon the time equivalency of stratigraphic units, even if their facies differ; (9) the depositional profiles and regional facies trends within a limited stratigraphic interval define the regional paleogeography.

Gressly provided the shoulders upon which other giants of stratigraphic science have stood. After Gressly, there were five additional stratigraphic concepts that were added to complete the current stratigraphic paradigm. These additional concepts were: (a) the stratigraphic process-response system conserves mass; (b) sediment volumes are differentially partitioned into facies tracts within a space-time continuum as a consequence of mass conservation; (c) cycles of facies tract movements laterally (uphill and downhill) across the earth's surface are directly linked to vertical facies successions, and are the basis for high-resolution correlation of stratigraphic cycles; (d) stratigraphic base level is the clock of geologic time, and the reference frame for relating the energy of space formation with the energy of sediment transfer; and (e) facies differentiation is a byproduct of sediment volume partitioning. Most of these were added around the turn of the century.

Acknowledgments

We thank Jean Paul Schaer and Marc Weidmann for reviewing our translation of Gressly. They also provided considerable insight on relevant historical and biographical matters. Their shared enthusiasm for this subject was stimulating. Michele Aldrich, Gerry Friedman and Gerry Middleton provided constructive reviews and directed our attention to some of the relevant literature. John Grotzinger read the penultimate draft and suggested improvements in the presentation. We appreciate their help. Elf Exploration Production gave permission to P. Homewood to publish this paper.

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“Description of terrains which compose the framework of the Jura Ranges in the Canton of Soleure and adjacent regions”

“The mountain ranges which run through the Soleure Canton and all of northwest Switzerland are composed, as in the French and Bernese Jura, of alternating hard and nonresistant limestones and marls which contain minor beds of siliceous, iron-rich, and other minerals. The number of stratigraphic units represented by these beds is greater, particularly in the north of the Canton and in the adjacent areas of Argovia and Basel Jura, than in the rest of the Swiss Jura. Besides the various oolithic groups, older stratigraphic units of the Triassic formation outcrop, showing sections of their tilted beds. These uplifted stratigraphic units in this area comprise the whole secondary [Werner’s Secondary, or stratified rocks] series from the variegated sandstones to the portlandian with a succession from base to top as follows:” 8/3-14

I. *Triassic or Conchylienne Formation, comprising the following terrains:*

1. Variegated sandstone terrain
2. Conchylian terrain or Muschelkalk
3. Keuper terrain or iridescent marls

II. *Jurassic or Oolithic Formation*

A) *Liassic Group*, subdivided into:

1. Lower Lias (sandstones of Lias and limestones with arcuate grypheas)
2. Upper Lias or Liassic marls

B) *Lower Jurassic or Lower Oolithic Group*, subdivided into:

1. Marly sandstone [written in English] and iron oolite
2. Compact and subcompact limestones [dense micrites and bioclastic] or Dogger
3. Dalles nacrées, rusty sandy limestones, Great Oolite [written in English], and marls with *Ostrea accuminata*

C) *Middle Jurassic Group or Oxfordian*, subdivided into:

1. Oxfordian marls or Oxford Clay [the latter written in English]
2. Terrain à chailles [cherty terrain]

D) *Upper Jurassic or Upper Oolithic Group*, subdivided into:

1. Coral terrain
2. Portlandian terrain

“This classification seems to me to be the most natural and most favorable for study of secondary [Werner’s Secondary] stratigraphic units of regions that we are concerned with because it provides broader divisions which are constant and avoids subdivisions that are artificial or purely local. It allows us to bring out better than any other complex descriptive system [classification] the essential characteristics of our stratigraphic units and their real relationships with analogs from foreign countries. Indeed, any descriptive system taken from foreign geologists and strictly applied to the study of a given distant country can lead to serious inconveniences [mismatches] which are easy to foresee for the Swiss Jura and which has been a common experience. Commonly that which is perfectly true for a broad stretch of country may not be appropriate for another area that is not very far away. And, it is only through careful study of all of the aspects of restricted areas, and then through comparison of several of these regions studied in this manner, that one at last arrives at general results. These results may allow a reasonable appreciation of the geological position [age] and more or less probable equivalence [stratigraphic correlation] of a particular rock [lithology], or a given stratal unit. This should serve as a solid basis for a well established and predictive knowledge of the manner, the conditions, and the laws of formation of these rocks and stratal units.” 9/12-32.

Brackets are used in the text either to give the French word translated, as in [”terrain”], or to clarify a translation so we did not stray too far from the literal French. Parentheses in the text are from Gressly. Italics in the text are from Gressly.

“In the areas that I have studied, perhaps more so than anywhere else, extremely varied petrographical or paleontological variations interrupt at every step the universal uniformity that was ascribed until now to the different stratigraphic units in the different countries. They [these variations] are even repetitive in several stratigraphic units [“terrains”], and cause astonishment for the geologist who attempts to study the nature of our Jurassic ranges.” 10/1-7

“Commonly, he [the geologist] will stop with surprise in front of formations he thought he knew well for a long time. Led astray by too much faith in accepted geological dogma, which often generalizes purely local facts, he will perhaps be mistaken about characters which until then he thought belonged only to a given stratigraphic unit and to a subdivision in particular; he even will be tempted to completely confuse several stratigraphic units going so far as to doubt their [separate] existence.” 10/8-14

“However, another more attentive study, more prolonged and above all more comparative, will show him how much the structure of our Jura is still unknown, facts which will open a new road to geological research and whose reach will only be measured when this research will have reached its full development and the results to which they lead will have been generally appreciated to their real value.” 10/15-20

“My intention was to apply to the country where I live the geological laws that Mr. Thurmann verified with so much talent and success on the stratigraphic units of the neighboring Bernese Jura; but soon I was forced to successively modify these laws according to the diverse regions which make up the Soleure Jura, and the study of these diverse regions necessitated on my part a system of research [research method] different to the one which is generally practiced. Instead of being satisfied with a certain number of vertical sections as type sections [“types descriptifs”], I followed each terrain along its horizontal extent as far as possible in order to study all its variations.” 10/21-29

“In this way, I have come to understand that within the areal extent [“dimension horizontale”] of each terrain, there are several well-defined variables which show the same features in petrographic composition as well as in the paleontologic attributes of their fossil content, and which are governed by specific and fairly constant laws.” 10/30-11/3

“Above all, there are two major facts which define everywhere the sum of the variables which I call *facies* or the *aspects of a stratigraphic unit*: one is that *within a stratigraphic unit the occurrence of a specific lithology necessarily also requires the occurrence of a specific paleontological association; and the other is that a given paleontological association rigorously excludes those genera and species of fossils which are frequent in other facies*.” 11/4-10

“If, by chance, certain genera and species which characterize a specific facies are found in another facies, it is a general rule that specimens of these genera and species will be much rarer, less developed and less characteristic than in the facies or general assemblage to which they normally belong. Similarly, wherever the geognostic characteristics of a facies [indicators of inferred depositional processes or environments] are best developed, the paleontological assemblages also are the best expressed, the genera and species are most numerous and individuals are most typical, best developed, and are commonly in a perfect state of preservation. If the facies show intermediate characteristics with mixed geognostic features, the fossils also share less typical attributes. In this case they are generally rare, poorly preserved, poorly developed and belong to few genera and species; however, there are occasional well-formed fossils which belong mostly to different species than those in the principal facies or which rarely occur in them.” 11/11-26

I will insist on these strange facts [i.e., paleontological and petrographical aspects related to facies] in the description of each stratigraphic unit that will be studied successively; because they seem to me to repeat at another scale and in different relationships a law similar to the one which governs the larger scale stratigraphic divisions. The subtle variations in faunal assemblages, related to lateral facies transitions, play a similar role within each small-scale time-stratigraphic unit, albeit on a vastly different scale, to that played by fossils of genuine stratigraphic value (such as the knotty Ammonite, the arcuate Gryphea, the Baculites) vertically within the larger-scale lithostratigraphic units. 11/27-12/3

“I think that the petrographic or paleontological changes of a stratigraphic unit in the horizontal are caused by the changes in environment and other circumstances, which still so powerfully influence today the different genera and species which inhabit the ocean and the seas. At least, I often have been astonished to find in the distribution of our fossils the laws of living communities and in the corresponding assemblages of petrographic and geognostic characteristics which correspond to the living communities, the environmental conditions which rule in the submarine world." 12/4-12

"Throughout the following descriptions of our stratigraphic units, I will give my interpretation on the different facies that I presume to be littoral—or shallow marine—deposits, or pelagic—or deep sea—deposits, however, without ascribing more confidence than the observational facts allow; because I expect to have to modify some points later after I have studied the entire terrain of our Jura from Randen in the Canton of Schaffhouse right down to the last Jura ranges beyond Geneva and from the Swiss [molasse] basin as far as the foot of the Vosges in the French departments of Doubs, Jura and Haut-Saône." 12/13-22

"I intend to return later to a more precise discussion of this subject after a deeper study of all the details of the combination of the paleontological constitution of our stratigraphic units and the phenomena within the marine environment today will allow me to judge with greater assurance and to give more justified opinion on these relationships." 12/23-28

"In the meantime, it is perhaps not out-of-place briefly to comment on my present way of understanding the correlations between the geognostic constitutions of stratigraphic units [the attributes allowing geological interpretation] and the fossil assemblages they contain." 12/29-31

"First of all, all the rocks of the sedimentary terrain of our Jura come under two main types: A) those which by their structure are essentially mechanical from a high energy sea, for instance, breccias, coarse oolite sand coquinas; B) or rocks which according to their structure are essentially *chemical* in origin from low energy seas, for instance marls, marly limestones, fine grained limestones, homogeneous limestones, more or less pisolitic limestones, and pisolites [perhaps oncolites] which grade into the matrix." 13/1-10.

"These two end member rock types, either pure or mixed, constitute well defined facies, according their petrographic characteristics, which vary according to their littoral or pelagic depositional environments. Their paleontological features are no less distinctive and always correspond even in the slightest detail to the geognostical [e.g. structure, bedding and stratification] and petrographic features, as we will see in what follows in treating each terrain in detail. I will only show here the major facies which are constant throughout all our stratigraphic units as far as I know their extent through my own observations, all the more so in that the more or less numerous local and transitional subfacies can easily be linked to the major facies." 13/11-21.

"Breccias, coquina, oolites, pisolites, mostly coarse grained, constitute the coral facies and associated deposits such as reworked sediment and immediate transitions to muddy facies. These rocks always show the characteristics of littoral and shallow marine deposits and only contain fossil assemblages which are characteristics of coral beds, mainly composed of fixed massive or branching corals, which resists the shock of waves and which living genera and species such as the Agaricias, Astreas, Oculinas, Caryophyllas, etc., today build coral banks and reefs in tropical seas that are so dangerous to ships. These corals always are accompanied by other organisms common to coral reefs, which appear to flourish in high energy, agitated water, thus always giving a morphology that provides resistance to the waves, the ones being firmly fixed to the substrate, the others having an extremely elastic structure which gives and bends in the force of the waves but recovers instantaneously, and comes out victorious from the incessant combat. The external morphology of the organisms and the layout of their organs are no less appropriate to the circumstances which govern their existence. Commonly all these properties are united to reach the objective." 13/22-14/10

"One finds as a characteristic example diverse Crinoids which are supported on a long stalk which is given elasticity and is more or less flexible through a number of articulated limestone disks which are held together by ligament fibers which are extremely flexible and are held inside a strong common epidermal sheath. They attach to the sediment surface and any body lying on it thanks to a large and ramified base or by holdfast. The Echinoderms above all those with spheroidal test or with a flattened disk which are made up of a multitude of plates which are joined together and can therefore support shocks abound in extremely varied species such as Cidaris, Diademia, and the Clypeastreas. The Spatangoids with the thin shell are to the contrary almost entirely absent." 14/11-22

“Among the Bivalves, there are genera of which a large number are solidly affixed to the substrate and other fixed objects. Among these are the Ostreas and the Spondyloids with a large basal foot and a strongly crenulate shell having many spines which help to anchor them to various objects on the seafloor. Others with a weaker shell lived in cavities, either those that happen to be there or those which were excavated by them within hard substrates. These are the Arcacea and the perforated genera such as Lithodomes and analogs to the Saxicavea, Venerupis, etc. Others protect themselves from the strength of the waves either by hiding in muddier environments sheltered by Corals and Crinoids, such as the Astartes and analogs, or by an excessive development of the carbonate shell like the Trichites, the Chamacea (Diceras), the Pernes, and some of the transition species of the muddy facies. Finally, others escaped the destructive attempt of the ocean by the high elasticity of their shell such as the Pectinids, the Limas, and the Terabratulids which in addition were supported by a strong ligament holdfast in the form of an elastic tendon.” 14/23-15/8

“Gastropods of the coral facies have the identical characteristics to the previous order. In particular, one finds the Turbo, Trochus, Pleurotomaria, some Nerinea, and a fairly large number of species of genera analogous to Monodontes, Patellas, Buccina, etc. Crustaceans, although not common, are not absent, in particular those close to the Pagurea, of which one only finds the strong pincers. To the contrary, Cephalopods and fish are rare; apparently reptiles are totally absent, and when they are found it is only by accident. Serpulids heavily encrust all bodies both organic and inorganic.” 15/9-19

“One very important characteristic which is universal to organisms within the coral facies is a very thick shell, always highly ornamented by ribs, striations, spines, nodes, and other ornamentation giving a strange, very particular physionomy, very irregular and useful for determining the niches they occupy in an ocean long gone from the surface of the earth.” 15/20-26

“The coral facies comprises several subfacies, which vary in the different stratigraphic units and regions of our Jura, and which are useful to know in order to understand the laws of distributions of paleontological associations. These subfacies are explained as transitions which link the major facies, and allow appreciation of the slightest nuances in the living conditions of the organic world now buried in the earth’s crust. Thus coquinas link petrographically the purely coral facies to the purely muddy facies, passing through the ooliths and pisoliths, to the sandy and gravely varieties [mixtures] of the muddy facies. Analogous passages from one paleontological assemblage to another always accompany these petrographic transitions. It is always the most delicate [“gracieuses”] forms which dominate in the transition zones.” 15/27-16/7.

“Reworked deposits, although closely related [spatially] to the coralline facies from which they mostly come, accompany and link all the facies, and don’t have, apart from a few genera of fossils which inhabit loose substrate, any characteristic zoological assemblage. They inherit, according to circumstances, some of the characteristics of the adjacent facies, receiving various fossil fragments which diminish in size as they are transported farther from their original habitat, finally to constitute an oolite [probably coated grains as opposed to ooids] or become entirely decomposed [lime mudstone or wackestone]. Using this observation, I have managed several times to follow the increase of debris size and conservation to find the original habitat. There, one finds the fossils in place, with a prodigious profusion and so well conserved that one can study the most minute details of the organization and characteristic assemblage, the behavior and habits, as we will see in the following descriptions of terrains.” 16/8-26

“The *muddy rocks*, such as marls, compact and subcompact limestone, finely granular and subcrystalline limestone with rare small ooids, passing gradually into concentric pisolites that are similar in composition to the matrix, [oncoids] sandstones, sands, etc. compose a second major facies, which is just as important as the preceding one, either from its extent within the Jura, which is much larger than the other, or according to the paleontological assemblages, which are radically different from the coralline facies. This facies is characterized geognostically by thinness [stratigraphic attribute] particularly in the nearshore parts, by the high variability of the deposits [lithological diversity] caused by local processes which in several stratigraphic units have given rise to numerous subdivisions [formations] which are only of interest for restricted areas. One rarely finds corals which are sponge-like genera and species which encrust and generally lack an obvious basal holdfast or with a very weak base when it does exist. Crinoids are rare, spread out, and belong to mostly to free-living forms. Echinoderms are a little less rare in particular the real Echinus and related genera. The Spatangoides are everywhere in the muddy rocks, but more in those which are gravely to sandy than in the genuine mudrocks. Asterids such as the genera Asteria and Saccocoma, are characteristic for the genuine mudrocks, as well as for the fine gravels and sands. There is commonly a prodigious quantity of free bivalves (Acéphales) in particular Solens, Pholadomya, Myopsis (Ag.), Jambonneaux, Tellina, Mytilus, Modiola, Corbula, and the analogs to the Isocarda, Cucullea, etc.; a large number Ostracea amongst which one can distinguish flat oysters which are weakly attached or free, Grypheas, and Exogyras, which are entirely free or fixed. Among the Gastropoda most common are the Rostellarias, the Pterocerids, Natica, and analogs to Turritella and Fasciolarids; among the Cephalopods, some Nautiloids, very diverse Ammonites and Belemnites, all rare or frequent, depending on the stratigraphic units and subfacies. Serpulids are rarer than in the previous facies. Crustaceans are represented by the genera Glyphea and analogs. Fish with broad flat teeth are characteristic of the mudrocks. Reptiles are found particularly in the Upper Jurassic terrains, but they are restricted to certain regions and isolated locations more than being ubiquitous. Their debris characterize above all the shoreline fringes of all Jurassic stratigraphic units and thus follow less strictly the facies laws, although they are not really abundant elsewhere than in the muddy littoral facies." 16/27-18/3

"A general trait, which is constant for all paleontological assemblages of the muddy facies, is that the dominant genera and species have tests less apt to resist destructive effects of reworking. The shells, among others, are normally very thin, very much smoother, less ornate, less ornamented with different protuberances than in the preceding [coral] facies where they have a very pronounced massive resistant character. However, there are sometimes genera and species with very thick shells but which have a less robust structure and which easily delaminate and disaggregate by abrasion." 18/4-13

"These phenomena are very obvious in the genera and species which are transitional from the coral to the muddy facies: thus the Trichites, the Pernes, and several other species, commonly have an enormously thick shell in the coral facies, whereas they only have a relatively thin test in the muds; similarly the Limas and the Pectinids, which are variously ornamented in the coralline facies with ribs, striations and spines, are generally almost smooth in muddy deposits, without talking about all the other remarkable differences which relate to their behavior in the different environments where local processes still too poorly known to be more precisely stated strongly influence the distribution and the structure of fossil organisms." 18/14-24

"Another distinctive characteristic of the fossils of the muddy facies is that they are almost exclusively free living genera and species. Even the Pentacrinids in these facies have never shown any trace of holdfasts, either their more or less lengthy stalk only has its lower extremity stuck in the mud, or they are held in place by extremely reduced byssal fibrils either in the mud or onto other objects lying on the seafloor. The spongy corals appear to behave similarly." 18/25-32

"Another facies of the muddy type belongs to the subpelagic and pelagic environments which has similar petrography to the littoral facies but differs by the characteristic fossil assemblage and by geognostic phenomena." 19/1-6

"The pelagic deposits are very constant, homogeneous, regularly stratified, very continuous or massive beds, very thick, lacking obvious structure; however, there are certain local exceptions to these features, for example, when reworked deposits cause perturbations and make the phenomena more difficult to decipher. Other causes unrelated to neptunian processes and which are not yet understood or which can only be suspected [diagenesis?] seem also to have strongly modified these deposits during deposition." 19/6-14

"What is most characteristic of these deposits is the almost complete lack of fossils over vast areas. As for corals, one only finds debris of fixed corals that have been worn and broken by rolling, or very poorly developed individuals; there are more numerous spongy corals with weak and soft fibrous tissue. It is generally accepted that these corals live at great depth, however, there is still doubt on this subject. In our terrains, they [deep water corals] are found at the transition between deep sea facies and littoral facies, more than in the pelagic facies strictly speaking. Some regions and localities even make me think that these zoophytes, under given circumstances, also lived on the muddy bottoms of localities that were sheltered from high waves such as in narrow and sandy gulfs and places behind coral reefs. In this case, they are always accompanied by more or less abundant fossils which are characteristic of subcoral and muddy littoral, such as free-living shells and certain Crinoids (Eugeniacrinus) and particular Echinoids. One could separate this assemblage from the pelagic facies under the name subpelagic *with spongy cor-*

als facies. But this separation will always be rather difficult, at least in our Jura, because this facies is so closely linked by imperceptible transitions to the true pelagic facies, if this facies could develop in the almost universal oceans of these ancient times, which were certainly much less deep than the Ocean and the seas of today.—Whatever, it is sure that with the appearance of the spongy corals, the fossils of the littoral facies successively disappear as one goes away from the ancient Vosges and Hercynian shorelines. In contrast, Belemnites and large Ammonites become more frequent, but they are very different from the littoral species (Macrocephalus and Planulates), whereas those of the littoral muddy facies are the Falciferes, Arietes and Ornates. Belemnites show similar modifications but less easily deciphered because of their unornamented shell. Of all the other organisms which are so abundant in all the littoral coral or muddy facies, there are now only a few Terebratulas, a few Ostracea and other similar fauna which seem to adapt to each given environment, but which show more or less obvious variations, the study of which should lead to very interesting results on the biological laws of ancient creations." 19/15-20/21

"After having determined the major facies which dominate our Jurassic terrains, it remains to take a look at the laws which underlie and control their distribution both vertically and horizontally." 20/22-25

"The facts that I have given above result in this first law:" 20/26-27.

"*Each facies of a stratigraphic unit has its own distinctive petrographic and geognostic or paleontologic attributes which do not represent the characteristics of the entire stratigraphic unit, nor the attributes of the other facies forming the same geological level* [stratigraphic interval]." 20/28-32 [italics from Gressly]

"This law will help correct the classifications of many stratigraphic units and their subdivisions by defining more precisely their position [stratigraphically and geographically], and will therefore avoid the serious mistakes in determining the geological level of localities [correlation of stratigraphic intervals] which are separated by large rock bodies with different characteristics." 21/1-4

"A second law is intimately linked to the first:" 21/5

"*Facies having the same petrographic and geognostic attributes show extremely similar paleontological characteristics throughout the stratigraphic succession* ["terrains"], *and occur in similar sequence through a variable number of superposed stratigraphic units*." 21/6-9 [italics from Gressly]

"I find this law to be of great interest with respect to the zoological [taxonomic?] determination of fossils and the use of taxa for paleontological characterization of stratigraphic units and their subdivisions. There is commonly great similarity between the morphologies of fossils of analogous facies, although they belong to very different stratigraphic units, and this resemblance has largely allowed the identification of many fossils in many terrains; this has led to a general concept that there are identical fossils not only in different subdivisions and groups of terrains, but even in formations separated one from another in the vertical stratigraphic column by other very thick and extensive ["très-vastes"] formations. A striking example of this sort, among others, is given by corals and Echinoderms, which although very similar at first glance, show to a well-trained anatomical zoologist very marked differences for each group [of fossils] and each stratigraphic unit in our Jura. Without wanting to solve the question of whether some fossils pass from one terrain to another, or even pass between stratigraphic groups, I would like to underline an important fact which has not been much considered that the external morphology of living organisms is always intimately related to their life environment, which Mr. Agassiz has demonstrated with perspicacity in his lectures." 21/10-30

"What I have said about vertical succession of facies is not without exception, and it is obviously natural that this law should vary according to the petrographic aspects and geognostics of rocks and stratigraphic units. We should thus not be surprised to find within a muddy rock above or below a coralline rock fossils which live in mud. But these fossils of the muddy facies will indicate no less than the corals a shallow marine or littoral environment even though these rocks are of a different type according to their depositional process." 21/31-22/6

"The distribution of facies either in the horizontal or in the vertical obeys other no less important laws." 22/7-8

"Sometimes *lateral ["horizontal"] facies transitions are abrupt, sometimes the transitions are gradual and one facies passes into another through intermediate varieties whose transitional features are poorly* *expressed, which together with the mixing of end-member facies, makes it difficult to separate them."* 22/9-13 [italics from Gressly]

"Abrupt facies transitions are particularly obvious between coral dominated facies and pure muds, above all when the coral beds are surrounded by subpelagic or pelagic deposits. In other cases this transition is more gradual and much less perceptible. This happens particularly between coral and muddy littoral facies which are commonly interspersed, as if their characteristics radiated from the centers or nuclei of rich organic growth out to the periphery which only shows broken debris or a few undifferentiated or poorly developed fossils." 22/14-23

"Diversity of the facies increases in a vertical direction from base to top throughout the whole series [stratigraphic succession through the Jurassic] *and, conversely, diminishes gradually in the opposite direction."* This law presents some very curious phenomena: in the lower part pelagic facies of muddy type predominate and the other facies only start to appear in a distinct manner from [at the stratigraphic position of] the Lower Oolite, which has features showing neither pelagic nor littoral characteristics but an obscure mix of both. We shall soon see what controls this phenomenon." 22/24-31 [italics from Gressly]

"Moreover, in some cases, following a considerable [thick and laterally extensive] pelagic deposit, littoral facies appear abruptly, almost without any gradual transition. This phenomenon, although infrequent, once again begins at the Lower Oolite. It coincides with the abrupt or gradual horizontal facies transitions of the stratigraphic units which I pointed out previously." 23/1-6

"*The diversity of facies is more or less constant in different regions.* The diversity increases in the regions where the French and Bernese Jura pass to the Argovian and Wurtemberg Jura; but once past this boundary the diversity successively diminishes as one goes farther away. Thus the western Jura mountains show more numerous variations in their essentially littoral composition than those which border the Swiss [molasse] basin toward the east and which tend to be more pelagic in nature. One could draw a line starting from Randen in the Canton of Schaffhouse as far as Chatelu in the Canton of Neuchâtel, running parallel to the foot of the Black Forest and the Vosges which would divide the littoral facies and the pelagic facies almost exactly into two separate parallel Jurassic zones. The western one which is larger, comprises most of Argovia, the Canton of Basel, the western ranges of the Blauen and of the Mont-Terrible in the Soleure and Bernese Jura, part of the mountain ranges between Delémont and Moutier, and almost the whole of the plateau of the Franches-montagnes. From there this swath continues toward the Chaux-de-Fonds, the Chatelu, where it loses part of its characteristics and only constitutes a very thin, irregular boundary between the pelagic deposits and the large Jurassic bay of the departments of Doubs and Haute Saône, which is almost entirely filled by littoral deposits which gradually thin from the Swiss border to the foot of the Vosges, showing paleontological characteristics which are increasingly littoral in all the terrains." 23/7-30 [italics from Gressly]

"The other zone which is pelagic, begins in Argovia and forms a less broad swath comprising the ranges of the Soleure and Bernese Jura which lie on the edge of the Swiss basin and the Tertiary valleys which run in to it. This swath is broader in the Canton of Neuchâtel and would seem to comprise the whole of the Vaud and Geneva Jura which only show enormously thick Portlandian domes [anticlines] with very few fossils." 23/31-24/5

"The subpelagic facies tract is intermediate between the littoral and pelagic facies tracts, and forms a transition zone more or less closely linking them. In the Canton of Schaffhouse and in Argovia this facies tract predominates with respect to the others, sometimes being more littoral sometimes being more pelagic, going from the Portlandian to the lower oolite through the Coralline Terrain and the two stratigraphic units of the Oxfordian. It is typically developed in the Soleure Canton and everywhere shows numerous Cnemidium, Tragos, Scyphia, etc. It is also shows the same features in the Neuchâtel Jura, etc. 24/6-14

"It is very remarkable that all the reentrants along this trend correspond to similar reentrants in the Jurassic shorelines along the Black Forest and the Vosges. For example, there are the reentrants of the pelagic facies in front of the Alsatian Gulf and the Bay of the Haute-Saône." 24/15-19

"This manner of studying and interpreting the composition of terrains, I find gives the following obvious advantages."

"1st. To reduce the extremely varied paleontological phenomena, which seem haphazard and without obvious coherence, to a limited number of very simple laws which are closely linked between each other and which relate to the mechanical aspects [process dependent physical aspects] of petrography and geognostics."

"2nd. To explain all these petrographical and geognostic attributes contained in sedimentary rocks, making them useful to science by carrying them from the realm of sterile [purely descriptive] mineralogy to the realm of geology by showing their relationships with the progressive development of life as is manifest at the different epochs of the history of our planet [evolution]."

"3rd. To be able to deduce with reasonable precision the relief of the seafloor [depositional profile] at various times until it becomes emergent, and also the various events which occurred in the ocean and which affected stratigraphic units and facies with higher or lower energy."

"4th. To be able to determine the timing of the various uplifts of a mountain range or a mountain chain through the littoral nature of the deposits which abut them." 24/20-25/7

"I still have to say a few words on how I will describe details of each terrain." 25/8-9

"To me it seems most desirable to follow a petrographical method based essentially on geological phenomena and the laws which govern them, rather than [a method based on] purely mineralogical characteristics; but in the present state of the science, this sort of a method is not possible or would be extremely speculative. I will follow, as far as possible, the descriptive approach adopted by Mr. Thurmann in his excellent "Essai sur les soulèvemens jurassiques du Porrentruy" apart from some modifications necessitated by the nature of the localities which I will describe. By thus following a uniform plan it will be possible to study as a single major work the series of memoirs that will be published in succession on the geology of the Jura Mountains carried out by people united in a single and same goal to increasingly understand the geological phenomena of our Jura which over the past few years has become so important to science." 25/10-22

"I will divide rocks into formations, groups and terrains, allowing further subdivision when necessary. Each of these divisions, clearly characterized both by petrography and paleontology, will be intimately linked. A brief abstrac*t* will precede the description of each formation, and in a similar fashion a *synopsis* will briefly characterize each group and each terrain with its different facies. *Synonyms* will indicate the equivalent terrains, divisions and facies of foreign countries if they exist and if they have been clearly described by geologists. A *listing* will indicate the geographical area of different stratigraphic units in our country. Finally, we will study the rocks themselves from two points of view, *petrographic* and *geognostic*. Thus we will have:

(a) a *petrographic* description which will give mineralogical composition and petrographic attributes of our rocks such as structure, attributes of a freshly broken surface, colors, cement, matrix, etc. These characteristics, of which incorrect use has been very damaging to the progress of geological knowledge, are no less extremely important in determining the different facies of an entire formation, a group, a terrain, or even a single bed, as we have previously seen by taking a rapid look at the petrographic composition of facies.

(b) a geognostic description, which will cover the phenomena of our rocks as a whole such as stratification, bedding, etc. These phenomena are more or less constant for each different facies; for example pelagic facies or reworked deposits are characteristically massive or thick bedded ["grande puissance"], whereas littoral deposits are less massive or thinly bedded. 25/23-26/18 [italics from Gressly]

"*Paleontology* will provide us with the principal characteristics of both large subdivisions and of facies. Study of fossilization and the substances which fossilize organisms, the state of preservation, and the distribution of fossils and their assemblages will provide observations and specific correlations with petrographical features as also found between different groups and stratigraphic units and various localities. 26/19-24 [italics from Gressly]

"Use of specific rocks and minerals from each terrain in technology, in agriculture, and their quarrying will not be forgotten, although the context of this geological essay will not allow lengthy commentary on this subject." 26/25-28